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Research Article

Understanding the Ageing Behaviour of the XLPE Cable Insulation Adopting LIBS Technique

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Abstract

The characteristic variations in the insulating behaviour of the XLPE cable insulating materials were investigated in the different ageing conditions using the LIBS technique. Plasma temperature and electron density were evaluated using the LIBS spectra of the XLPE cable sample after its accelerated ageing in the aqueous solution of the $BaCl_2$, NaCl, $CuSO_4$ and acid rain. Further, electron beam irradiation followed by the accelerated ageing in different solutions were performed on the samples and its plasma properties was examined. The plasma temperature and electron density decreased for the different solution aged specimen and increased for the electron beam irradiated XLPE samples. Recovery in the plasma temperature and electron density was observed for the dried sample after the completion of ageing process in the different solutions.

Keywords: accelerated ageing, electron beam, LIBS, plasma properties, XLPE cable.

1. Introduction

HVDC cables are widely being used for power transmission and among all crosslinked polyethylene (XLPE) insulating more popular because of its good electrical and mechanical properties [1-3]. However, its operation can be restricted due to different electrical, mechanical, moisture, and thermal factors which could possibly initiate the different degradation process resulting into the reduction of the different insulating behaviour of the power cable insulation [4]. Furthermore, as the need for electricity grows, renewable energy is becoming a more viable option for generating electricity, and offshore energy, in particular, is increasingly being used to generate electric power and transmit it to onshore power stations through undersea power cables. These submarine cable insulations are used in an extremely hostile environment beneath the sea, which affects the cable insulation's insulating properties over time [5]. As a result, it is very much critical to comprehend how the XLPE cable insulating material behaves under ageing circumstances that are similar to those seen under the sea. Wang et al. studied the water needle initiated electrical treeing process in the XLPE cable insulation and concluded that the presence of the solution can lead to the enhancement in the electric field at the tree tip which consequently led to the diversification of the electrical trees [6]. Zhou et al. presented the conversion mechanism of the electrical trees to water trees in the XLPE cable insulation. In the presence of the moisture the electrical tree tip became the initiation site for the formation of water trees [7].

Furthermore, power cables are widely being utilized in nuclear power plants, resulting in a significant risk of these power cables being exposed to various radiation, which can modify the varied insulating qualities of the cable insulation [8]. As a result, it is very important to comprehend the effects of various levels of radiation on cable insulation behaviour.
Based on the literature review, it is clearly understood the importance of characterizing the cable insulating materials in different ageing conditions. Laser induced breakdown spectroscopy (LIBS) is a non-invasive diagnostic method for qualitative and quantitative elemental characterization of materials [9,10].

LIBS is gaining more importance because of its fast measurement capability, remotely access technique with accurate measurement, non-availability of sample preparation [11]. Gondal et al. utilized the LIBS technique for the identification of different elements present in the HVDC cable which can be the potential cause for the initiation of the water trees [12].

Having known all the above aspects, the present work is focused on the (a) accelerated ageing of the XLPE cable insulation in the aqueous solution of $BaCl_2$, NaCl, $CuSO_4$ and acid rain, (b) LIBS analysis of the aged samples in different solutions and electron beam irradiated samples, (c) variation in the plasma temperature and electron density of the aged samples and dried samples after performing the accelerated ageing of the XLPE samples.

2. Experimental studies

2.1 LIBS analysis

The LIBS experimental setup is shown in Figure 1. A Q-switched Nd^{3+}:YAG laser source (LAB-150-10-S2K, Quanta-Ray LAB series, Spectra Physics) was used to generate a laser beam with a wavelength of 1064 nm and a pulse duration of 10 ns. In this study, the laser energy was varied by varying

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the Q-switch time delay and it was set at 30 mJ for all types of aged and unaged XLPE samples. A focusing lens (L_1) with a focal length of 25 cm was utilized to focus the laser beam on the XLPE sample surface. As the plasma generated, optical emission occurred, which was focused using a second focusing lens (L_2) with a focal length of 100 cm, and transferred to the spectrometer (Ocean Optics USB2000 + UV–VIS-ES) using optical fiber with a core diameter of 400 µm and numerical aperture 0.22.

2.2 Accelerated ageing and Electron beam irradiation

In this study, 1M of aqueous solution containing Sodium Chloride (NaCl), Barium Chloride ($BaCl_2$), Copper sulphate ($CuSO_4$), and acid rain were prepared and then accelerated ageing of the XLPE cable insulation with a thickness 10 mm was carried out by immersing the samples in each kind of solution and keeping the solution containing samples in oven with a temperature set at 90º C. Table 1 lists the chemical constituents found in acid rain, along with their mass concentrations. During the accelerated ageing process weight of the XLPE cable insulation was continuously monitored and very minimal change in the weight was observed in all kind of aqueous solutions and acid rain.

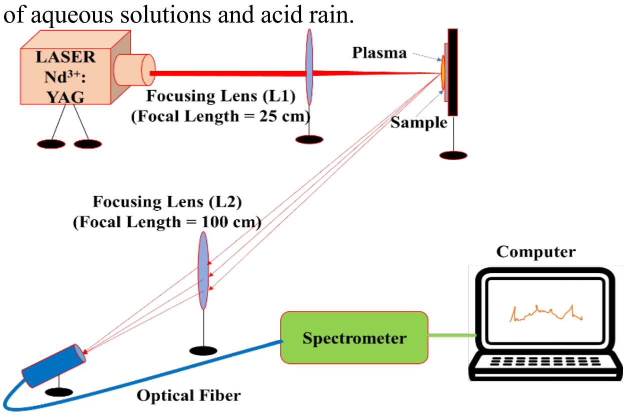

Fig. 1. Experimental setup for LIBS analysis.

Before the XLPE cable insulation was immersed in the various aqueous solutions, it was thoroughly cleaned with ethanol to remove any kind of surface impurities. Further, some set of the samples were taken out of the solution after almost saturation in its weight and kept for drying in order to carry out the LIBS experiment. In addition, certain group of XLPE samples was irradiated with electron beam rays at a dosage rate of 4.5 kGy/h for total doses of 100 kGy, 200 kGy, 300 kGy, and 400 kGy. Further the accelerated ageing of the irradiated samples was performed as discussed above.

Table 1. Chemical constituents of the acid rain.

Chemical compounds	Acid rain (g/2l)
KCl	0.18
NaCl	2.55
NH_4Cl	1
$CaSO_4$	1.05
HNO_3	0.90
$MgSO_4$	1.05

3. Results and discussion

3.1 LIBS Spectra

Figure 2 illustrates the LIBS spectra for the virgin sample and for the XLPE cable insulation after performing its accelerated ageing in different solutions. For each experiment, average of 20 LIBS spectra was captured at different positions of the sample. Further NIST Atomic Spectra Database was utilized to identify the different elemental peak present in the LIBS emission spectra [13]. Peaks of elements N(I), N(II), C(II), O(I), O(II), Si(I), and Si(II) were identified in the emission spectra of a virgin sample. Extra peaks of Ca(I), Cu(I), and Na(I) were found in acid rain aged XLPE samples due to the presence of $CaSO_4$, $CuSO_4$, and NaCl in the Acid rain solution which get diffused into the XLPE cable insulation during the accelerated ageing process. Furthermore, an extra peak of Cl(II) was seen in the $BaCl_2$ aged sample, an extra peak of Na(I) and Cl(II) in the NaCl solution aged sample, and an extra peak of Cu(I) in the $CuSO_4$ aged sample.

Also, after ageing, different elemental peaks were observed to get slightly reduced and more reduction was observed in case of the sample aged in the $CuSO_4$ solution. After the ageing of the cable insulation in different solutions, samples were allowed to get dried and emission spectra was captured. It was observed that dried samples elemental peak intensities magnitude regained to the intensity's magnitude of the virgin sample.

3.2 Plasma Temperature and Electron Density

At local thermodynamic equilibrium, plasma temperature (T_e) was calculated using the Boltzman-Saha equation [14] for virgin and aged samples based on its spectral intensities,

$$T_e = 1.44 \frac{E_2 - E_1}{\ln\left(\frac{I_1 \lambda_1 A_2 g_2}{I_2 \lambda_2 A_1 g_1}\right)} \quad (1)$$

Where, E_1 and E_2 are excited energy levels, λ_1 and λ_2 are the wavelengths of the atomic elements corresponding to the spectral intensities I_1 and I_2 respectively. g_1 and g_2 refers to the respective statistical weight of the excited energy levels E_1 and E_2 having the transition probabilities of A_1 and A_2 respectively. Depending on the plasma temperature at the instant of plasma creation, the electron density (n_e) was calculated using the modified Saha equation [15],

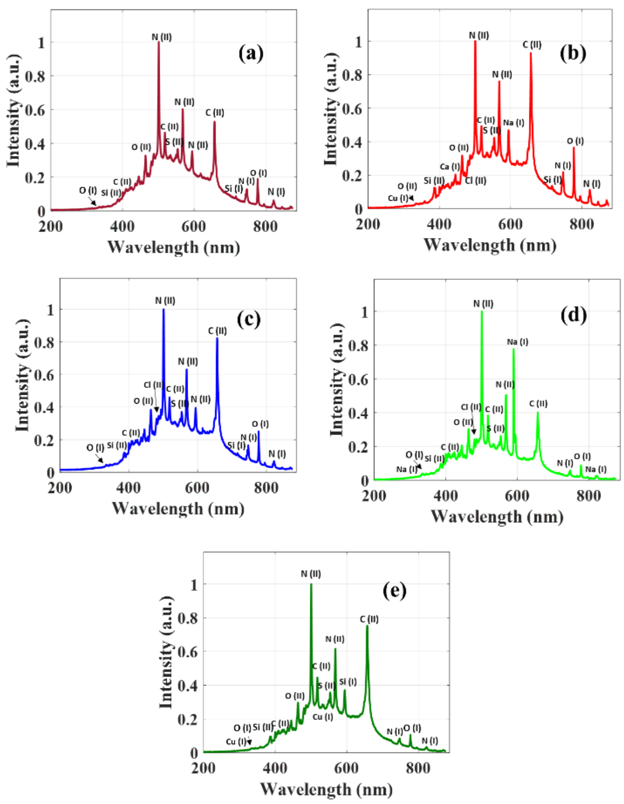

Fig. 2. LIBS Spectra of (a) Virgin sample, (b) Acid rain, (c) $BaCl_2$, (d) NaCl, and (e) $CuSO_4$ solution aged sample.

$$n_e = 6.6 \times 10^{21} \times \frac{I_1 A_2 g_2}{I_2 A_1 g_1} \times \exp\left[-\frac{E_{ion} + E_2 - E_1}{kT_e}\right] \qquad (2)$$

Where E_{ion} refers to the first ionization potential and k refers to the Boltzmann constant.

Figure 3 shows the variation in the plasma temperature and electron density of the XLPE cable insulation of the virgin and accelerated aged samples in different solutions. Plasma temperature was found to be lower for the aged XLPE cable insulation samples and sample aged in the $CuSo_4$ solution has lowest plasma temperature. After ageing of the samples, it was left for drying, and further plasma temperature and electron density was evaluated based on the spectral intensities of the LIBS spectra. Drying of the samples lead to the increment in the plasma temperature and corresponding electron density also regained its value. Recovery of the plasma temperature was more for the XLPE sample aged in the $CUSO_4$ solution. Plasma temperature is the indirect indication of the hardness of the material [9]. During the laser ablation process, harder materials will have less ablated mass on incident of the laser beam on the material surface. These ablated mass act as a heat sink as a result harder the material, lesser will be the mass ablation resulting into the increment of the plasma temperature. During the accelerated ageing of the material, different aqueous solution would diffuse into the free volume of the materials leading to the mobilization of the different polymeric chains which actually loosens the polymeric bond in the XLPE cable insulation. These alteration in the polymeric bonds would be more dominant on the surface of the insulating materials resulting into the decrement in the hardness of the materials and consequently plasma temperature declined. Presence of $CuSO_4$ in the aqueous solution accelerated the chain scission process leading to more degradation of the surface of the XLPE insulating materials and hence lowest plasma temperature was observed for the aqueous $CuSO_4$ solution aged sample. Furthermore, for the aged samples, electron density followed the same decreasing trend as plasma temperature. Electron density represents the number of free electrons which got detached from its atom per unit volume and it was lowest for the $CuSO_4$ solution aged samples.

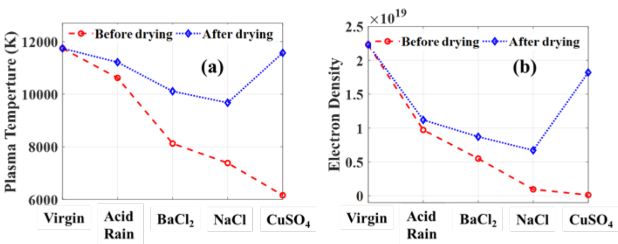

Fig. 3. (a) Plasma Temperature, and (b) Electron Density of the aged samples.

3.3 Electron Beam Irradiated XLPE Cable Insulation

Further the effect of the electron beam irradiation on the plasma temperature and electron density of the XLPE cable insulation was evaluated. LIBS spectra were captured for the sample irradiated with the different dosage of electron beam rays and further plasma temperature and corresponding electron density was determined as shown in the Figure 4. It was observed that increment in the dosage level of the electron beam increased the plasma temperature and electron density. Exposure to the electron beam rays initiated different crosslinking and oxidation phenomena in the materials, and at higher dosage level crosslinking phenomena would be more dominant over the oxidation phenomena leading to the formation of carbonyl group which lead to the increment in the surface hardness of the materials and consequently plasma temperature and electron density increased [16].

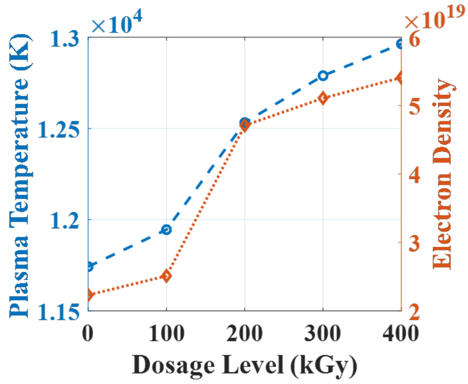

Fig. 4. Plasma Temperature and Electron Density of the electron beam irradiated samples.

Accelerated ageing of the electron beam irradiated samples were performed in the aqueous solution of the $BaCl_2$, NaCl, $CuSO_4$ and acid rain, and plasma temperature and electron density of the samples were evaluated using Boltzmann-Saha equation. Figure 5(a) shows the variation in the plasma temperature and electron density of the 300 kGy electron beam irradiated sample aged in different solution. As discussed above accelerated ageing of the XLPE cable in solution lead to the decrement in the plasma temperature and electron density, so similar trend was observed for the electron beam irradiated samples. For the samples immersed in the different solution, the decrement in the plasma temperature and electron density value for the irradiated sample was less as compared to the unirradiated samples. As the crosslinking phenomena due to the electron beam irradiation will increase the bonding strength as a result degradation due to the different solution ageing would be less resulting into the minimal reduction in the polymeric strength of the materials and hence plasma temperature and corresponding electron density was higher for the irradiated samples as compared to the unirradiated samples after its accelerated ageing in different solutions. Also, the effect of the presence of $CuSO_4$ in the aqueous solution was more dominant as compared to the other solutions, hence plasma temperature and electron density was minimal for the sample aged in same solution even after electron beam irradiation. After ageing process completed, plasma properties were calculated for the dried samples and minimal enhancement in the plasma temperature and electron density was observed for all the solutions except for $CuSO_4$ solution. Plasma temperature and electron density was almost equal to original one for the irradiated sample dried after immersion in $CuSO_4$ solution. So, the $CuSO_4$ solution was chosen to analyze its effect on the plasma properties of the XLPE cable insulation irradiated with the different dosage level of electron beam rays and the variation in the plasma temperature and electron density is shown in Figure 5(b). Very minimal variation in the plasma temperature and electron density was observed with increment in the dosage level of the electron beam rays and recovery in the plasma temperature and electron density was there for the dried samples, and plasma properties was highest for the samples irradiated with the electron beam with the dosage level of 400 kGy. At higher dosage level crosslinking phenomena would be more dominant leading to the enhancement in the bonding strength of the polymeric bond and hence less degradation on immersing the samples to the $CuSo_4$ solution, and consequently plasma properties were highest at the dosage level of 400 kGy for the dried samples.

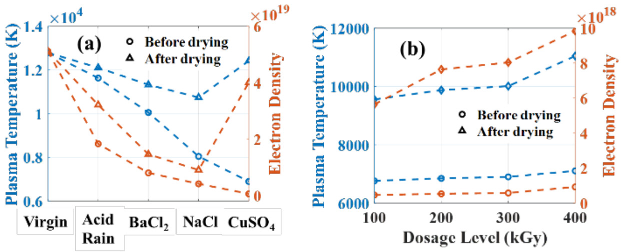

Fig. 5. Plasma Temperature and Electron Density of the (a) 300 kGy irradiated sample aged in different solution, and (b) $CuSO_4$ solution aged samples at different dosage level of electron beam.

4. Conclusions

The following are important findings of this research work: -

1. Accelerated ageing of the XLPE cable insulation in the aqueous solution of $BaCl_2$, NaCl, $CuSO_4$ and Acid rain led to the decrement in the LIBS peak intensities of spectra.
2. Plasma temperature and electron density decreased after ageing of the samples in different solutions and plasma properties was minimum for the samples aged in the $CuSO_4$ solutions. Plasma temperature and electron density increased for the samples dried after accelerated ageing conditions.
3. Plasma temperature and electron density increased for the electron beam irradiated samples, and it increased with the increment in the dosage level of the electron beam rays.
4. Combined effect of the electron beam and accelerated ageing of the XLPE cable insulation in different aqueous solution on the plasma temperature and electron density was analyzed. XLPE samples immersed in the different solutions, the decrement in the plasma temperature and electron density value for the irradiated sample was less as compared to the unirradiated samples. Also, minimal enhancement in the plasma temperature and electron density was observed for the dried samples except for the $CuSO_4$ solution aged samples.
5. Degradation of the unirradiated and electron beam irradiated samples was more in the $CuSO_4$ solution.

5. Acknowledgement

The author (RS) dedicate this manuscript to Prof. Toshikatsu Tanaka's 82nd Birthday occasion.

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